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ROLE OF Hf AND Zr IN THE HYDROGEN EMBRITTLEMENT OF Ta AND Cb ALLOYS

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TECHNICAL PAPER proposed for presentation at
Conference on Hydrogen in Metals: Effects on Properties, Selection, and Design sponsored by the American Society For Metals
Champion, Pennsylvania, September 23-27, 1973

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EMBRITTLEMENT OF Ta AND Cb ALLOYS

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E-6988

INTRODUCTION

Alloys of Ta and Cb are of interest as containment material for alkali liquid metals. In the presence of oxygen contamination concentrated at grain boundaries in such alloys as Ta-10W, severe corrosion results due to preferential attack of the high oxygen content regions by alkali metals. Because of this corrosion problem, additions of reactive elements such as Hf or Zr are made to Ta and Cb alloys to getter the oxygen. It has been shown (1) for a Ta alloy, T-111 (Ta-8W-2Hf), that corrosion was essentially nil after aging for several thousand hours in an alkali metal environment. However, recent results have indicated (2) that long term aging of T-111 near 1040°C (a proposed use temperature for this alloy) increases its sensitivity to hydrogen embrittlement during subsequent room temperature handling and testing in the presence of moist air.

The purpose of this paper is to further characterize the hydrogen embrittlement of aged T-111 and similar Ta and Cb alloys and to describe the mechanisms believed responsible for the increased sensitivity of T-111 to low temperature hydrogen embrittlement after aging for 1000 hours or longer near 1040°C. A total of eight Ta base alloys and two Cb base alloys were investigated. The effects of pre-age annealing temperature, aging time, temperature and environment, and alloy composition on the susceptibility to hydrogen embrittlement were investigated. The primary method of determining the effects of these variables on the ductility of T-111 was by bend testing at 25° and -196°C. Fractured specimens were examined by the scanning electron microscope, electron microprobe, metallography and X-ray diffraction.

TABLE I. - CHEMICAL ANALYSIS OF TANTALUM AND COLUMBIUM ALLOYS

Alloy nominal composition, weight percent	Ta	Cb	W	Hf	Zr	Other	C	H	N	O
	Content, weight percent						Content, ppm			
Ta-10 W	Bal.	----	10.35	----	----	-----	15	1.0	40	21
Ta-2 Hf	↓	----	-----	1.9	----	-----	22	1.0	39	33
Ta-8 W-0.5 Hf	↓	0.04	7.8	.51	0.02	-----	50	1.0	9	30
Ta-8 W-1 Hf	↓	.04	8.0	.9	.03	-----	50	1.6	5	24
Ta-8 W-2 Hf (T-111)	↓	.05	8.5	2.0	.06	-----	50	2.9	15	120
Ta-8 W-3 Hf	↓	.04	8.2	2.8	.09	-----	60	1.0	8	28
Ta-4 W-2 Hf	↓	.04	3.8	1.8	.06	-----	50	0.8	7	26
Ta-8 W-1 Re-0.7 Hf-0.025 C (ASTAR 811C)	↓	----	7.5	.65	----	1.0 Re	260	3.0	32	25
Cb-1 Zr	----	Bal.	----	----	0.95	-----	100	3.0	70	73
Cb-10 Hf-0.9 Ti-0.5 Zr-0.4 Ta-0.4 W-0.015 C (C103)	0.4 ↓		0.4	9.8	.52	0.95 Ti	<30	<5	40	130

EXPERIMENTAL PROCEDURE

The chemical analyses of the alloys investigated in this study are given in Table I. The primary alloy under investigation in this program, T-111, was purchased in the form of sheet having a thickness of 0.8 mm and in the form of tubing having a 19 mm outside diameter and a 0.8 mm wall thickness. The remaining alloys were custom melted and fabricated to 0.8 mm thick sheet. Longitudinal bend specimens 6.4 mm X 25.4 mm were cut from the alloys. A standard annealing treatment for the Ta alloys consisted of 1-hour at 1650°C plus 1-hour at 1315°C. The Cb alloys were annealed at equivalent homologous temperatures, 1345° and 1070°C, respectively. In order to determine the effects of annealing temperature on subsequent hydrogen embrittlement, T-111 specimens were also annealed for 1-hour at 1815 or 1980°C plus 1-hour at 1315°C. A standard aging treatment for all ten alloys consisted of heating at 1040°C (the temperature which was associated with previous hydrogen embrittlement) for 1000 hours. One half of the specimens from each alloy were sealed in a T-111 capsule containing lithium while the remaining half of the specimens were tied to the outside of the capsule and heated in an ultrahigh vacuum of 1.3 X 10^{-7} N/m^2. In addition a series of T-111 specimens were aged for 1000 hours at 925°C and a second series at 1150°C in order to bracket the primary aging temperature of 1040°C. A final series of T-111 specimens was aged for 5000 hours at 1040°C to determine the effect of aging time on subsequent hydrogen embrittlement.

After aging, removal of the lithium from the capsules was achieved by vacuum distillation or by dissolution in liquid ammonia. Several specimens from each alloy were then doped with approximately 10 ppm hydrogen by heating at 1040°C in a partial pressure of hydrogen of approximately 13 KN/m^2 for 10 minutes.

Primary evaluation of the alloy specimens was by means of bend testing at 25° and -196°C. Specimens were tested in a screw driven testing machine at a punch rate of 25.4 mm per minute. A bend radius of 2t and a total bend angle of about 160° was used for all the tests. After completing the bend test, specimens were then flattened so that in effect the tests were a 180°, 0t bend. Specimens were tested in the annealed and aged conditions before and after hydrogen doping.

After testing fracture surfaces were observed by scanning electron microscopy utilizing characteristic X-ray analysis to identify particles present on the fractured surface. In addition particles were identified by use of the electron microprobe and by X-ray diffraction of extracted particles. Standard light microscopy, transmission electron microscopy and scanning electron microscopy were utilized to characterize the microstructures of the alloys.

To further characterize the effects of aging on T-111 several specimens having different aging histories were also examined metallographically. Their aging conditions will be given at the appropriate place in the Results section.

RESULTS

Bend Tests

The effects of various annealing and aging conditions on the bend ductility of T-111 sheet and tubing are summarized in Table II. Specimens in the annealed condition or after aging at 925° and 1150°C underwent a full 180° - 0t bend at -196°C. All specimens aged at 1040°C independent of pre-age annealing temperature or aging time were brittle at -196°C. Testing tube specimens at 25°C resulted in ductile behavior for all conditions except for the specimen that had been annealed at 1980°C prior to aging. These results show that T-111 is susceptible to aging embrittlement over a narrow temperature range near 1040°C.

The effect of hydrogen doping on T-111 sheet and tubing is also summarized in Table II. Sheet T-111 in the annealed condition could undergo the full 180° - 0t bend test; however, surface cracks were observed on the specimen. A sheet specimen aged at 925°C could be bent 90° at -196°C prior to failure while a specimen aged at 1150°C was brittle upon testing at -196°C. The remaining sheet specimens and all tube specimens doped with approximately 10 ppm hydrogen were brittle at 25°C. The tube specimens appear to be more susceptible to hydrogen embrittlement, in agreement with previous results (2) where it was observed that aged tube samples were more susceptible than aged sheet samples

TABLE II. - EFFECT OF AGING CONDITIONS AND HYDROGEN DOPING ON

BEND DUCTILITY OF T-111 (Ta-8 W-2 Hf)

Annealing temperature, °C	Aging conditions			Bend test	
	Time, hrs	Temperature, °C	Environment	Temperature, °C	Results
Sheet					
1650	----	----	-------	-196	Ductile
1650	1000	925	Lithium	-196	Ductile
1650	1000	1150	Vacuum	-196	Ductile
1650	5000	1040	Lithium	-196	Brittle
1650	1000	1040	Vacuum	-196	Brittle
1815	1000	1040	Lithium	-196	Brittle
1980	1000	1040	Vacuum	-196	Brittle
Sheet - Hydrogen Doped					
1650	----	----	-------	-196	Cracks
1650	1000	925	Vacuum	-196	90° bend
1650	1000	1150	Lithium	-196	Brittle
1650	5000	1040	Vacuum	25	Brittle
1650	1000	1040	Lithium	25	Brittle
1815	1000	1040	Vacuum	25	Brittle
1980	1000	1040	Lithium	25	Brittle

Annealing temperature, °C	Aging conditions			Bend test	
	Time, hr	Temperature, °C	Environment	Temperature, °C	Results
Tube					
1650	1000	925	Vacuum	-196	Ductile
1650	1000	1150	Lithium	-196	Ductile
1650	5000	1040	Vacuum	-196	Brittle
1650	5000	1040	Vacuum	25	Ductile
1650	1000	1040	Lithium	-196	Brittle
1650	1000	1040	Lithium	25	Ductile
1815	1000	1040	Lithium	-196	Brittle
1815	1000	1040	Lithium	25	Ductile
1980	1000	1040	Lithium	-196	Brittle
1980	1000	1040	Lithium	25	Brittle
Tube - Hydrogen Doped					
1650	1000	925	Vacuum	25	Brittle
1650	1000	1150	Lithium	25	Brittle
1650	5000	1040	Lithium	25	Brittle
1650	1000	1040	Vacuum	25	Brittle
1815	1000	1040	Lithium	25	Brittle
1980	1000	1040	Vacuum	25	Brittle

TABLE III. - EFFECT OF ALLOY COMPOSITION ON AGING EMBRITTLEMENT AND

SUBSEQUENT SUSCEPTIBILITY TO HYDROGEN EMBRITTLEMENT

Condition	Hydrogen doped	Bend test	
		Temperature, °C	Results
Ta-10 W			
Annealed	No	-196	Ductile
Aged*	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Cracks
Ta-2 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Ductile
Ta-8 W-0.5 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-1 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-2 Hf (T-111)			
Annealed	No	-196	Ductile
Aged	No	-196	Brittle
Aged	No	25	Ductile
Annealed	Yes	-196	Cracks
Aged	Yes	25	Brittle
Ta-8 W-3 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Brittle
Aged	No	25	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	25	Brittle
Ta-4 W-2 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-1 Re-0.7 Hf-0.025 C (ASTAR 811C)			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Cb-1 Zr			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Ductile
Cb-10Hf-0.9Ti-0.5Zr-0.4Ta-0.4W (C103)			
Annealed	No	-196	Ductile
Aged-vacuum	No	-196	Cracks
Annealed	Yes	-196	Ductile
Aged-vacuum	Yes	-196	Cracks

*Aged 1000 hours at 1040° C.

to moisture in the bend test atmosphere. The results indicate that aging over the temperature range 925° to 1150°C increases the susceptibility to hydrogen embrittlement of T-111 compared to the annealed condition

The effects of alloy composition on the aging and hydrogen embrittlement of Ta and Cb alloys are summarized in Table III. The results indicate that aging embrittlement in Ta alloys occurs only in T-111 (Ta-8W-2Hf) and the alloy Ta-8W-3Hf. The Cb alloy, C103 exhibited slight surface cracks in the aged condition which may be attributed to aging embrittlement. All the annealed alloys doped with hydrogen were ductile at -196°C with only the T-111 specimen exhibiting slight surface cracks as a result of the 180° -

0t bend. With the exception of Ta-2Hf and Cb-1Zr all the aged alloys were susceptible to hydrogen embrittlement. The binary Ta alloy, Ta-10W, and the Cb alloy, C103, exhibited surface cracks when tested at -196°C. Tantalum alloys T-111 (Ta-8W-2Hf) and Ta-8W-3Hf were brittle at 25°C upon testing in the aged plus hydrogen doped condition. The remaining alloys that were aged in lithium prior to hydrogen doping were brittle at 25°C while those aged in vacuum underwent the 180° - 0t bend and exhibited only surface cracks. The reason for this ductility dependency on aging environment was shown to be related to a higher concentration of hydrogen in those specimens aged in lithium compared to those aged in vacuum. Oxygen analysis after aging showed that lithium removed oxygen from the modified T-111 alloys while vacuum aging had no apparent effect on the oxygen content. Subsequent hydrogen doping under identical conditions showed a greater pickup of hydrogen in the low oxygen content (lithium aged) specimens (about 20 ppm compared to 10 ppm for vacuum aged) and hence the more brittle behavior at 25°C.

The results indicate the Ta and Cb binary alloys, especially Ta-2Hf and Cb-1Zr are not embrittled at -196°C as a result of the 1040°C aging plus hydrogen doping. In contrast the more complex aged Ta alloys are all embrittled by hydrogen when tested at 25°C while the complex Cb alloy, C103, suffered some loss of ductility at -196°C.

Metallography

The aging embrittlement and increased susceptibility to hydrogen embrittlement of aged Ta alloys is attributed to the change in microstructure upon long time aging near 1040°C. Aging T-111 for 1000 hours at 980°C results in formation of rows of precipitate particles lying along grain boundaries as shown in the transmission electron micrograph of figure 1(a). In contrast aging for 1000 hours at 1315°C results in a microstructure free of precipitates as shown in figure 1(b). This microstructure is characteristic of annealed T-111 as well. Results of electron microprobe step-scan traverses along grain boundaries of annealed and aged T-111 are shown in figure 2. The annealed T-111 shows minor variations of Ta, W and O along grain boundaries; however, in the aged material, peaks of Hf and O were observed while the W remained constant. These results suggest the particles observed in figure 1 are Hf rich. X-ray diffraction results of particles remaining from dissolution of an aged T-111 specimen showed the residue to be HfO_2.

The effects of alloy composition of Ta alloys on fracture behavior and precipitate morphology are shown in figure 3. All specimens were aged 1000 hours at 1040°C, doped with hydrogen and bend tested at 25°C. It should be noted that Ta-10W and Ta-2Hf, figure 3(a) and (b), fail in a ductile manner and are free of precipitate particles at grain boundaries. Alloys shown in figure 3(c) and (d), Ta-8W-.5Hf and Ta-8W-1Hf, respectively, are seen to fail primarily in a brittle manner with some evidence of ductile failure. The Ta-8W-2Hf (T-111) and Ta-8W-3Hf alloys fracture in a completely brittle manner, as shown in figure 3(e) and (f), respectively. Precipitate particles are observed in all four of these ternary alloys with the amount of particle formation increasing with increasing Hf content. Use of an energy dispersive spectrometer on the scanning electron microscope showed that on the grain boundary surface in T-111 Hf could not be detected, figure 3(g), while the particles at the grain boundaries are Hf rich as shown in figure 3(h). Observations on the two Cb alloys showed that they failed in a ductile manner with no apparent formation of precipitates at grain boundaries

DISCUSSION

The aging and hydrogen embrittlement of T-111 and other similar Ta base alloys is believed to be due to Hf segregation at grain boundaries. The absence of particle formation in Ta-2Hf suggests that the presence of W in the ternary alloys affects the rate and degree of Hf segregation that is observed in these alloys. This may occur due to the lattice contraction that occurs upon adding W to Ta (3) causing the larger Hf atom to segregate to mifit or grain boundary areas. Competing with this equilibrium segregation process is diffusion which will tend to evenly disperse the solute at higher temperatures (4). Hence, T-111 aged at 1315°C did not exhibit precipitate particles as was shown in figure 1(b). Also this material did not exhibit aging embrittlement and was not susceptible to hydrogen embrittlement.

The role of Hf in Ta alloys and probably Zr or Hf in more complex Cb alloys in the hydrogen embrittlement problem is to segregate to grain boundaries during aging thus causing embrittlement at -196°C. Doping the aged material with hydrogen contributes an additional embrittling effect which is evident by the brittle behavior at 25°C of aged and hydrogen doped specimens. It appears that Hf segregation compounds the embrittlement caused by hydrogen since no embrittlement was observed in Ta-2Hf where Hf did not segregate. This increased embrittlement may arise due to Hf segregated at grain boundaries acting as a sink for hydrogen causing hydrogen to segregate at grain boundaries as well, in the ternary and more complex alloys.

For use as containment materials for alkali metals the ternary alloys Ta-8W-.5Hf, Ta-8W-1Hf, and Ta-4W-2Hf were not susceptible to aging embrittlement, thus suggesting they are more attractive than

T-111 (Ta-8W-2Hf). These alloys were susceptible to hydrogen embrittlement after aging. In contrast Ta-2Hf was not susceptible to aging or hydrogen embrittlement and should also provide corrosion resistance. Results from this study indicate the tensile strength of Ta-2Hf is about 50 percent that of T-111 (Ta-8W-2Hf) at 1040°C which may limit its use at this temperature. The Cb alloys should also be considered as possible candidates based on their favorable ductility after aging and hydrogen doping.

CONCLUSIONS

Based on a study of the hydrogen embrittlement of aged Ta and Cb alloys the following conclusions are drawn:

1. Aging ternary Ta alloys such as T-111 (Ta-8W-2Hf) near 1040°C for 1000 hours or longer increases their sensitivity to low temperature hydrogen embrittlement.

2. Segregation of Hf to grain boundaries during aging causes embrittlement upon testing at -196°C and is responsible for the observed hydrogen embrittlement.

3. Binary Ta and Cb alloys, Ta-2Hf and Cb-1Zr, are not susceptible to hydrogen embrittlement under the conditions of this study and did not exhibit grain boundary segregation of Hf or Zr.

4. Ternary alloys Ta-8W-.5Hf, Ta-8W-1Hf, and Ta-4W-2Hf are superior to T-111 for containment of alkali metals in that they do not exhibit aging embrittlement. However, these alloys in the aged condition are susceptible to hydrogen embrittlement. Binary alloys Ta-2Hf and Cb-1Zr are attractive containment materials based on retention of low temperature ductility after aging and hydrogen doping; however, their relatively low tensile strengths at 1040°C may limit their use.

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4. McLean, D.: Grain Boundaries in Metals. Oxford at the Clarendon Press, 1957.

TABLE I. - CHEMICAL ANALYSIS OF TANTALUM AND COLUMBIUM ALLOYS

Alloy nominal composition, weight percent	Ta	Cb	W	Hf	Zr	Other	C	H	N	O
	Content, weight percent						Content, ppm			
Ta-10 W	Bal.	----	10.35	----	----	-----	15	1.0	40	21
Ta-2 Hf		----	-----	1.9	----	-----	22	1.0	39	33
Ta-8 W-0.5 Hf		0.04	7.8	.51	0.02	-----	50	1.0	9	30
Ta-8 W-1 Hf		.04	8.0	.9	.03	-----	50	1.6	5	24
Ta-8 W-2 Hf (T-111)		.05	8.5	2.0	.06	-----	50	2.9	15	120
Ta-8 W-3 Hf		.04	8.2	2.8	.09	-----	60	1.0	8	28
Ta-4 W-2 Hf		.04	3.8	1.8	.06	-----	50	0.8	7	26
Ta-8 W-1 Re-0.7 Hf-0.025 C (ASTAR 811C)		----	7.5	.65	----	1.0 Re	260	3.0	32	25
Cb-1 Zr	----	Bal.	----	----	0.95	-----	100	3.0	70	73
Cb-10 Hf-0.9 Ti-0.5 Zr-0.4 Ta-0.4 W-0.015 C (C103)	0.4		0.4	9.8	.52	0.95 Ti	<30	<5	40	130

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TABLE II. - EFFECT OF AGING CONDITIONS AND HYDROGEN DOPING ON

BEND DUCTILITY OF T-111 (Ta-8 W-2 Hf)

Annealing temperature, ^{o}C	Aging conditions			Bend test	
	Time, hrs	Temperature, ^{o}C	Environment	Temperature, ^{o}C	Results
Sheet					
1650	----	----	-------	-196	Ductile
1650	1000	925	Lithium	-196	Ductile
1650	1000	1150	Vacuum	-196	Ductile
1650	5000	1040	Lithium	-196	Brittle
1650	1000	1040	Vacuum	-196	Brittle
1815	1000	1040	Lithium	-196	Brittle
1980	1000	1040	Vacuum	-196	Brittle
Sheet - Hydrogen Doped					
1650	----	----	-------	-196	Cracks
1650	1000	925	Vacuum	-196	90^{o} bend
1650	1000	1150	Lithium	-196	Brittle
1650	5000	1040	Vacuum	25	Brittle
1650	1000	1040	Lithium	25	Brittle
1815	1000	1040	Vacuum	25	Brittle
1980	1000	1040	Lithium	25	Brittle

Annealing temperature, ^{o}C	Aging conditions			Bend test	
	Time, hr	Temperature, ^{o}C	Environment	Temperature, ^{o}C	Results
Tube					
1650	1000	925	Vacuum	-196	Ductile
1650	1000	1150	Lithium	-196	Ductile
1650	5000	1040	Vacuum	-196	Brittle
1650	5000	1040	Vacuum	25	Ductile
1650	1000	1040	Lithium	-196	Brittle
1650	1000	1040	Lithium	25	Ductile
1815	1000	1040	Lithium	-196	Brittle
1815	1000	1040	Lithium	25	Ductile
1980	1000	1040	Lithium	-196	Brittle
1980	1000	1040	Lithium	25	Brittle
Tube - Hydrogen Doped					
1650	1000	925	Vacuum	25	Brittle
1650	1000	1150	Lithium	25	Brittle
1650	5000	1040	Lithium	25	Brittle
1650	1000	1040	Vacuum	25	Brittle
1815	1000	1040	Lithium	25	Brittle
1980	1000	1040	Vacuum	25	Brittle

TABLE III. - EFFECT OF ALLOY COMPOSITION ON AGING EMBRITTLEMENT AND SUBSEQUENT SUSCEPTIBILITY TO HYDROGEN EMBRITTLEMENT

Condition	Hydrogen doped	Bend test	
		Temperature, °C	Results
Ta-10 W			
Annealed	No	-196	Ductile
Aged*	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Cracks
Ta-2 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Ductile
Ta-8 W-0.5 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-1 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-2 Hf (T-111)			
Annealed	No	-196	Ductile
Aged	No	-196	Brittle
Aged	No	25	Ductile
Annealed	Yes	-196	Cracks
Aged	Yes	25	Brittle
Ta-8 W-3 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Brittle
Aged	No	25	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	25	Brittle
Ta-4 W-2 Hf			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Ta-8 W-1 Re-0.7 Hf-0.025 C (ASTAR 811C)			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged-lithium	Yes	25	Brittle
Aged-vacuum	Yes	25	Cracks
Cb-1 Zr			
Annealed	No	-196	Ductile
Aged	No	-196	Ductile
Annealed	Yes	-196	Ductile
Aged	Yes	-196	Ductile
Cb-10Hf-0.9Ti-0.5Zr-0.4Ta-0.4W (C103)			
Annealed	No	-196	Ductile
Aged-vacuum	No	-196	Cracks
Annealed	Yes	-196	Ductile
Aged-vacuum	Yes	-196	Cracks

*Aged 1000 hours at 1040° C.

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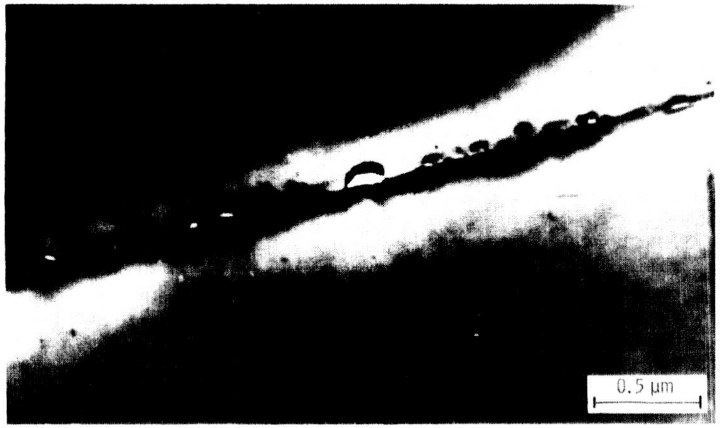
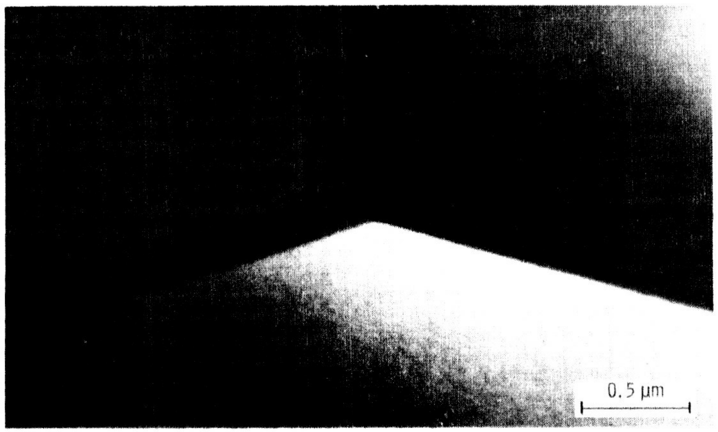
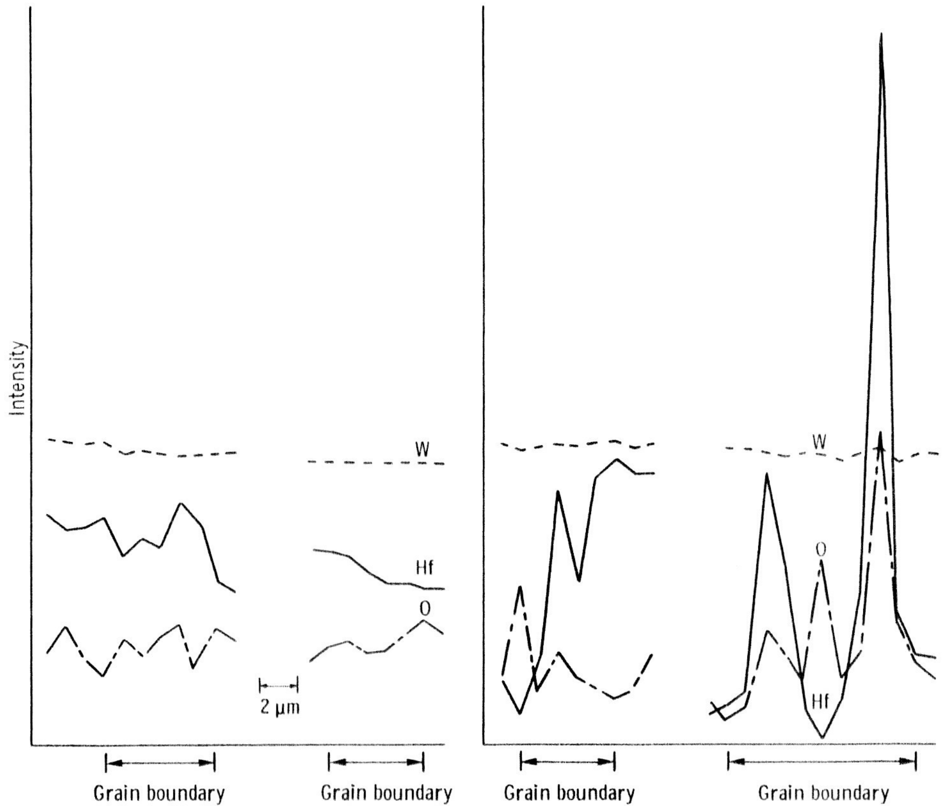


(a) AGED 1000 HOURS AT 980^{0} C IN LITHIUM.



(b) AGED 1000 HOURS AT 1315^{0} C IN LITHIUM.

Figure 1. - Transmission electron micrographs of aged T-111 sheet.

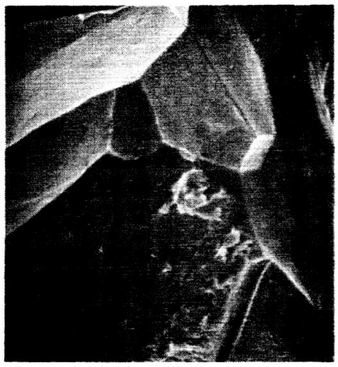


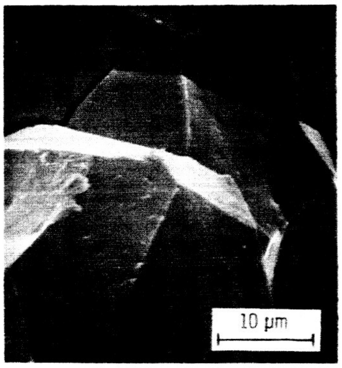
(a) Annealed.

(b) Aged 10 000 hours at 1040^{0} C.

Figure 2. - Electron microprobe step-scan traverses of annealed and aged T-111 tubing.

(a) Ta-10W. (b) Ta-2Hf.

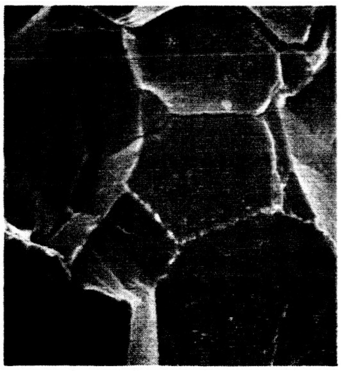


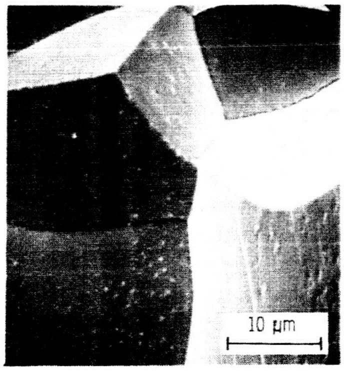


(c) Ta-8W-0.5Hf. (d) Ta-8W-1Hf.

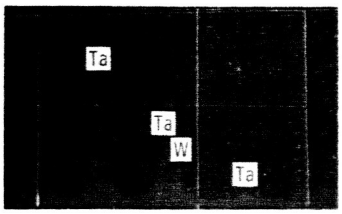
Figure 3. - Scanning electron microscope observations and analysis of precipitate particles in 1000 hour - 1040° C aged Ta alloys.

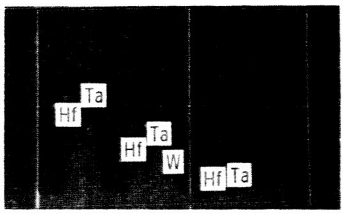
E-6988





(e) Ta-8W-2Hf. (f) Ta-8W-3Hf.





(g) GRAIN BOUNDARY SURFACE. (h) PARTICLE.

Figure 3. - Concluded.